Adaptation of Pulse Crops to the Changing Climate of the Northern Great Plains

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ABSTRACT

Climate over the northern Great Plains has generally warmed over the last 60 yr. The rate of warming has varied temporally and spatially, confounding trend analysis for climate indicators such as increased length of the growing season. Change in precipitation has been even more variable. Despite this variability, present-day trends in temperature and precipitation generally coincide with the predicted direction of climate change. The synchrony of current and future trends reinforces the need for investigating adaptation in agriculture to changing climate. Our review is focused on sustainability of pulse crops in the northern Great Plains and the repercussions of climate change, focusing on the growth and yield response to temperature and water, and the climate restrictions that define their current geographic locations. The resilience of pulse crops to present-day weather extremes such as drought, excess water, heat, cool weather during grain filling, and early frost are considered to predict adaptation to future climate change. Features discussed include changes to crop water-use efficiency brought on by increased CO_2 fertilization, accelerated growth rates resulting from higher air temperatures, and total crop failures caused by an increased occurrence and magnitude of weather extremes. Adaptation strategies that are discussed include earlier seeding of pulse crops, use of winter pulses, crop sequencing within crop rotations, and alterations to the microclimate such as direct seeding into standing stubble.

Interest in pulse crops (annual legumes) by northern Great Plains producers has risen sharply in the recent decades. Pulses included in this review are soybean (*Glycine max* L.), dry pea (*Pisum sativum* L.), lentil (*Lens culinaris* Medik.), and chickpea (*Cicer arietinum* L.). Soybean production is concentrated in the southeastern region of the northern Great Plains, that is, the subhumid regions of South and North Dakota (Fig. 1). Dry pea, lentil, and chickpea production is concentrated in the semiarid regions of the northern Great Plains in both Canada and the United States (agroecoregions 1 and 12, Fig. 1), but especially in Canada. Dry bean (*Phaseolus vulgaris* L.) is a warm-season crop similar to soybean. Although we did not focus on dry bean in our review, we recognize the increased breeding efforts in adapting dry bean to the northern Great Plains and the expanded production of dry bean in recent years. There is clear evidence that the climate of the northern Great Plains has warmed, especially over the past 50 to 60 years. Climate trends in temperature and precipitation have had and will continue to have significant impact on agriculture. For example, climate warming has had a significant impact on the rapid increase of pulse adoption to the Northern Plains. In this review, we focus on the environmental requirements of pulses, historic climate change and simulations of future climate change, and simulations of crop response to proposed climate change. We provide recommendations for research of current and developing technologies to enhance pulse adaptation to future climates.

ADOPTION AND ROLE OF PULSE CROPS

Climatic conditions vary tremendously within the northern Great Plains, including long, cold winters; short, warm summers; large diurnal ranges in temperature; frequent strong winds; highly variable and unpredictable precipitation (Padbury et al., 2002). The precipitation uncertainty and temperature extremes are serious risks to agriculture on the Plains. However, pulse crops provide producers with opportunities to diversify cropping systems and assist with managing the risk of unpredictable weather and market patterns (Zentner et al., 2002; Miller and Holmes, 2005). Pulse crops also complement cropping systems such as no-till or direct-seeding. The adoption of pulse crops has enabled producers to reduce summer fallow and increase cropping intensity because of improved soil conservation and increased soil water availability (Larney et al., 1994). The diversification and intensification of no-till cropping systems have significantly contributed to increase environmental and economic sustainability (Zentner et al., 2002). Pulse crops increase market diversification since their prices respond somewhat independently of cereal grain markets (Zentner et al., 2002). Pulse crops increase production diversification due to differential responses to growing season rainfall and temperature patterns (Johnston et al., 2002; Miller et al., 2002a). The inclusion of pulses in crop rotations often increases the efficiency of cereal crop production (Johnston et al., 2002; Miller et al., 2002a).

The area sown to pulse crops in the northern Great Plains has increased steadily in the last two decades (Miller et al., 2002a). The most notable area for increased production has been in semiarid regions of the Canadian Prairies, where dry pea, chickpea, and lentil are used to extend the traditional wheat-fallow crop rotations, especially in no-till management systems. In 2002, pulse crops accounted for 24% of seeded area in the Brown soil zone of Saskatchewan, an increase from 4% in 1991 (Statistics Canada). The increased production of pulse crops on the Canadian prairies (30% between 1978 and

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Published in Agron. J. 99:1684–1699 (2007).
Symposium Papers
doi:10.2134/agronj2006.0310s

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Abbreviations: ET, evapotranspiration; GCM, global climate model; WUE, mean water use efficiency.

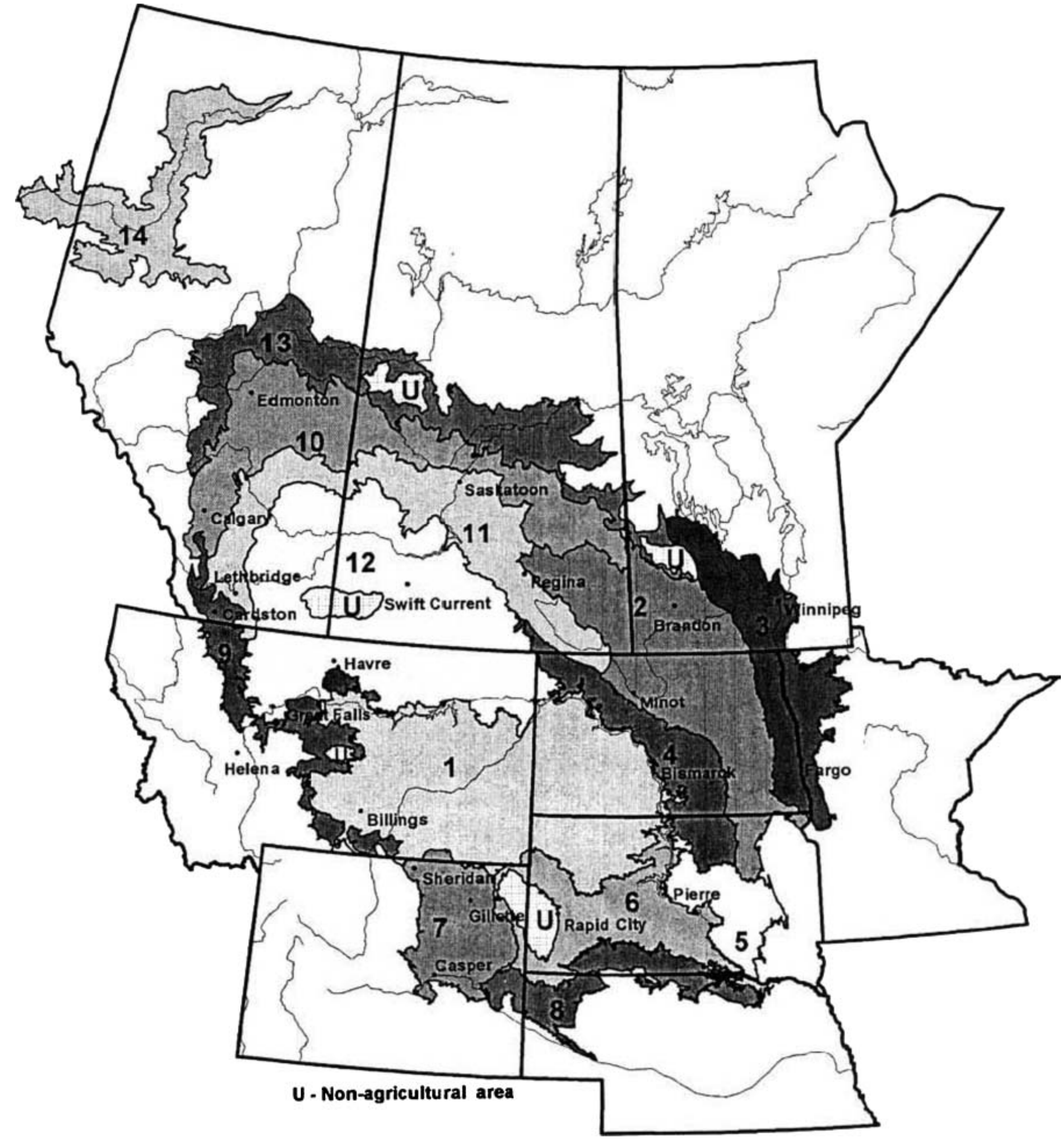

Fig. 1. Agroecoregions of the northern Great Plains (from Padbury et al., 2002) including the provinces Alberta, Saskatchewan, and Manitoba in the Canadian Prairies; and Montana, Wyoming, North Dakota, South Dakota, Nebraska, and Minnesota of the United States. For a description of the Agroecoregions 1 to 14, see Padbury et al. (2002).

1999) has occurred at the expense of fallow, which has declined dramatically (Miller et al., 2002a). The introduction of dry pea, lentil, chickpea to the northern Great Plains of the United States has progressed at an accelerated rate recently. However, soybean remains the most important pulse crop grown in the northern Great Plains, but because of a long growing season, soybean production is largely restricted to South Dakota and Nebraska on the southeastern edge of the Plains.

Cause and Effect of Accelerated Climate Change

Over the past 50 to 60 yr, accumulating evidence suggests that human activities have contributed significantly to stimulating global climate change (Schneider, 1994; Skinner and Majorowicz, 1999; Intergovernmental Panel on Climate Change, 2001; Smith and Almaraz, 2004), and will continue to do so well into the 21st century (Karl et al., 1997). "The Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change, 2001) projects that atmospheric concentrations of CO_2 will increase from 368 μmol mol^{-1} in 2000 to between 540 and 970 μmol mol^{-1} in 2100. Over the same period, the IPCC estimates that accumulation of atmospheric greenhouse gases will increase air temperatures 1.4 to 5.8°C. Important regional variations will underlie these global trends" (White et al., 2004). For example, most of the evidence provided by trend analysis of long-term weather data and by climate change models suggests that climate is warming over the northern Great Plains (Karl et al., 1996; Zhang et al., 2000b). As well, many already dry regions across the earth may experience a decrease in precipitation, while other regions may receive increased precipitation. These changes will have varying and complex impacts on agricultural production. The severity of climate change effects on crop production depends on the magnitude of the temperature increase; modeling indicates that increases up to 2.5°C will cause variable effects on the agriculture sector. Temperature increases $\leq$2.5°C may promote increased agricultural production in the cooler temperature regions of the earth but decrease production in the warmer tropical regions. Temperature increases above 2.5°C will generally have negative overall effects on world agriculture (Intergovernmental Panel on Climate Change, 2001; Smith and Almaraz, 2004). "Field experiments using elevated CO_2 concentrations of 550 μmol mol^{-1} typically show increased yields of well-watered and fertilized crops of 10 to 20%. Benefits of elevated CO_2 are even greater for water deficits, but yield increases under nitrogen deficits are lower than for fertile conditions" (White et al., 2004; Kimball et al., 2002).

Adapting to a Changing Climate

Ecological responses to climate change are already visible (Cayan et al., 2001; Walther et al., 2002; Parmesan and Yohe, 2003). In general, spring activities have occurred progressively earlier since at least the 1960s (Walther et al., 2002). The impact of global warming is discernable in both animal and plant biology. For example, averaged across several hundred temperate-zone species (including plants and animals), the shift in spring phenology, such as breeding or blooming, is about 5 d earlier in each decade during the past half century (Root et al., 2003). Satellite imagery has shown that between 1982 and 1999 the beginning of spring is 8 ± 4 d earlier in North America and the duration of the active growing season increased by 12 ± 5 d (Zhou et al., 2001), especially for forests, tundra, and grasslands between 30° and 80°N (Keeling et al., 1996). In western North America, earlier spring onsets since the late 1970s are a common feature of phenological and temperature records, and reflects the recent spell of warmer-than-normal springs (Cayan et al., 2001).

"The goals of adaptation strategies are to improve the knowledge and skills of farmers, to encourage adoption of new technologies, and to expand the array of options available to farmers" (Motha and Baier, 2005). However, because of the given uncertainties and serious consequences of potentially inaccurate assessments of climate change and the required adaptation strategies, Motha and Baier (2005) recommended aggressive study and research into how best to limit and mitigate the impacts of climate change on agriculture. They further caution that complacency is very risky and advise vigorous effort toward understanding and preparing for potentially serious impacts on agriculture by developing adaptation strategies.

PULSE CROPS AND THE NORTHERN GREAT PLAINS

Response to Environment

Temperature

The maturity requirements of dry pea, lentil, and chickpea are easily met at most locations in the northern Great Plains (Miller et al., 2002a). The mean cumulative degree-days at a base of 5°C (DD_5) required for early maturing soybean (00 maturity group) exceed the mean cumulative DD_5 available at many locations in the northern Great Plains except for South Dakota and Nebraska (Miller et al., 2002a). Desi chickpea (480 DD_5), dry pea (530 DD_5), and lentil (540 DD_5) require fewer degree days to reach anthesis, compared with spring wheat (600 DD_5) (Miller et al., 2001, 2002a). Dry pea (1010 DD_5) generally attains maturity sooner than spring wheat (1070 DD_5), while lentil (1060 DD_5) mature earlier than spring wheat only in years when near-normal climatic conditions have occurred. Chickpea (1120 DD_5) generally matures slightly later whereas soybeans (1590 DD_5)[1] mature substantially later than spring wheat.

Pulse crops may be categorized into cool-season (dry pea, lentil, and chickpea) and warm-season (common bean and soybean) crops based primarily on their ability to emerge in cool soil conditions and on frost tolerance (Miller et al., 2002a). Minimum temperatures for seed germination and crop growth differ among pulse crops, with soybean having a base temperature near 10°C (Raper and Kramer, 1987), compared with base temperatures near 0°C for chickpea, dry pea, and lentil (Roberts et al., 1988; Summerfield et al., 1989; Ney and Turc, 1993). Consequently, soybean typically requires a relatively later seeding date, mid-May to early June in most locations in the northern Great Plains, to reduce the risk of frost injury. Chickpea, dry pea, and lentil tolerate a moderate degree of frost, −2 to −18°C, depending on cultivar, degree of acclimation, and plant stage (Wery et al., 1993; Welbaum et al., 1997; Srinivasan et al., 1998). If a severe frost kills the shoot, axillary nodes below the soil surface generate new shoots. The resultant loss of plant vigor reduces yield potential but typically does not require reestablishment of the field because a late seeding date also has a reduced yield potential (Miller et al., 2002a). Early spring seeding will improve dry pea productivity in the Canadian semiarid prairies (Johnston et al., 1999). In a spring seeding date study at Swift Current, SK (1993–1998), frost injury was never observed in dry pea, lentil, or desi chickpea despite seedling exposure to −5 to −6°C in 4 of 6 yr (Miller et al., 1998), indicating that there is little risk to very early seeding of these cool-season pulse crops. Similarly, at Swift Current, SK, Gan et al. (2002) found early seeded chickpea and pea yields were on average 13 and 20% higher, respectively, than late-seeded yields. They concluded seed yields of both chickpea and dry pea in a semiarid environment can be enhanced by man-

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[1] Most soybean cultivars are short-day plants, and thermal time to anthesis can be greatly extended at long day-length periods (Miller et al., 2002a).

agement practices that promote early seedling emergence, prolonged reproductive period, and increased pod fertility.

On the Canadian Prairie, daytime temperatures for best growth of chickpea range from 21 to about 30°C whereas the temperature range for best growth of field pea is 13 to 23°C (Hnatowich, 2000; Soltani et al., 2006; Wang et al., 2006). Temperatures exceeding 30 to 32°C limit yield of chickpea by hastening maturity and/or by decreasing seeds/plant and seed weight (Harris, 1979; Wang et al., 2006). Chickpea will tolerate higher temperatures than field pea during flowering; temperatures $> 27°C$ will often decrease flower numbers and flowering duration for field pea (Hnatowich, 2000; Hawthorne et al., 2003). Lentil has poor tolerance for high temperatures, especially at flowering and pod set (Erskine et al., 1994).

Water

Currently available chickpea and lentil cultivars have an indeterminate growth habit and require physiological stress (i.e., drought) to terminate flowering and induce seed set (Saskatchewan Pulse Growers, 2000). This can result in significant risk for many locations in the northern Great Plains in years with wetter-than-normal growing conditions combined with an early fall frost. Seeding in early spring allows cool-season pulse crops, especially the early maturing field pea, to complete a larger portion of their growth cycle during the late spring and early summer rainy season before the onset of summer drought, which typifies the northern Great Plains, and thus minimize production risk (Miller et al., 2002a). Also, early spring seeding of chickpea and lentil enable better timing for termination of flowering and induction of seed set by the terminal droughts typifying late summer.

Cool-season pulse crops are more suited to semiarid regions of the northern Great Plains (Miller et al., 2002a). Angadi et al. (1999) compared the plant water relations among chickpea, dry pea, and lentil at Swift Current, SK, and found all three pulse crops used less water than spring wheat. Averaged across water regimes and years, spring wheat used 296 mm water compared with 278 mm for chickpea and 266 mm for dry pea. Dry pea and lentil are well adapted to semiarid Plains regions where the soil profile is often only shallowly recharged with water. Chickpea extracted more water from the soil profile than field pea or lentil (Miller et al., 2003a; Zhang et al., 2000a), especially from below 0.30 m (Angadi et al., 2003). Lentil and dry pea rooting systems effectively extracted water in the upper 0.9 m of soil while chickpea (desi type) used soil water to 1.2 m (Zhang et al., 2000a; Nielsen, 2001; Siddique et al., 2001; Angadi et al., 2003; McKenzie et al., 2004).

The mean water use efficiency (WUE) of dry pea is generally similar to that of spring wheat (Borstlap and Entz, 1994; Angadi et al., 1999; Miller et al., 2002a, 2003a), whereas the mean WUE values for all other pulse crops are generally lower than that of spring wheat (Angadi et al., 1999; Siddique et al., 2001; Miller et al., 2002a). Soybean, a warm-season pulse, has the lowest mean WUE (Miller et al., 2002a), reflecting a typically delayed seeding date and longer plant maturity, extending crop growth into the mid- and late-summer season when peak evapotranspiration (ET) demand occurs. As such, soybean generally is not as suitable to include in dryland cropping systems in semiarid regions of the northern Great Plains, especially in western regions where rainfall peaks in the late spring and early summer, not in late summer.

Pulses are generally most susceptible to water stress during the later half of the growing season (the reproductive stage), but especially during flowering and seed set (Haskett et al., 2000; Nielsen, 2001; Siddique et al., 2001). In environments where water shortages can occur at any time during the growing season and terminal droughts predominate, high-yielding genotypes tend to flower early, pod early, and have a relatively long flowering period (Siddique et al., 2001; Gan et al., 2002; Berger et al., 2004; Turner et al., 2005). Thus, drought escape is an important phenological characteristic at sites with terminal (late-season) drought. However, where drought is severe throughout the entire growth period, substantial biomass redistribution is associated with high yield, suggesting that physiological mechanisms in addition to rapid phenological development play a role in the adaptation of pulses to water-limited environments (Gan et al., 2002; Berger et al., 2004; Turner et al., 2005). Once stressed, even for short periods, water-stress-induced acceleration of senescence cannot be stopped by eliminating the stress, and short periods of water stress during seed filling may have larger-than-expected effects on yield (Brevedan and Egli, 2003).

Lentil, and to a lesser extent chickpea, have shown limited yield benefit from irrigation on the northern Great Plains (Angadi et al., 1999). The benefits of irrigation are somewhat dependent upon late-summer, fall weather. Warmer, drier weather during seed set and filling hastens maturity, reducing the risk of fall frost injury which can reduce seed yield and seed quality.

Cropping Systems: Rotations and Crop Sequencing

Crop sequencing within crop rotations can have a significant impact on the productivity of succeeding crops, and thus, on the productivity of the crop rotation as a whole. Research suggests producers would benefit by investing considerable thought towards cropping system design to meet the needs of their particular operations. Including pulse crops in a crop rotation affects wheat yield through a series of complex interactions on soil water, soil nutrient supply, and interruption of pest cycles (Miller et al., 2002a). Wheat yield responses can vary considerably depending on previous pulse crops, years, and locations (Table 1). Generally, most reports indicate positive effects by the previous pulse crop on a succeeding wheat crop, either through conservation of soil water and/or soil N. However, the effect of pulse crops on succeeding crops is complex and not well understood. For example, the extra N from the previous pulse crop is only beneficial for the subsequent crop when moisture is sufficient to utilize the increased N and where

Table 1. Effect of the previous crop's residue on spring wheat yield. Normalized grain yield and protein response of hard red spring wheat seeded the following year into either fallow, legume stubble, or spring wheat stubble in three studies in the northern Great Plains (adapted from Miller et al., 2002a).

	Carrington, ND (1991–1993)		Swift Current, SK (1993–1997)		Williston, ND (1996–1998)	
Crop residue	Yield	Protein	Yield	Protein	Yield	Protein
Fallow check	170	119	–	–	126	102
Dry pea	161	114	125	108	101	108
Lentil	131	114	123	108	97	109
Chickpea	146	114	119	108	–	–
Soybean	133	114	–	–	–	–
Spring wheat†	100	100	100	100	100	100
High-N control‡	181	118	–	–	–	–
SE	8	3	5	1	9	4

† Mean grain yield were 1.5, 1.9, and 1.8 Mg ha^{-1}; mean grain protein concentrations were 118, 142, and 142 g kg^{-1} for spring wheat grown on spring wheat stubble at Carrington, Swift Current area, and Williston, respectively. Mean N fertilizer applications were 0, 50, and 86 kg N ha^{-1} for all wheat grown at Carrington, Swift Current area, and Williston, respectively.

‡ High-N control spring wheat (grown of spring wheat stubble) received 106 kg N ha^{-1}.

N is yield limiting (Miller et al., 2002a). Proper sequencing of pulses within rotations can have long-term positive yield and economic benefits for producers when good crop management practices including control of weeds, diseases and other pests, and timely seeding to better match crop phenology with seasonal water availability patterns are practiced.

Dry pea, chickpea, and lentil have good potential for diversifying cropping systems in the dry semiarid prairie (Miller et al., 2001). Miller et al. (2001) found dry pea grain yields averaged 103% of wheat when grown on fallow and 135% of wheat when grown on wheat stubble. Chickpea, lentil and dry pea yielded 76, 77, and 90%, respectively, of their fallow-field yields when grown on stubble, indicating that the pulse crops have excellent potential for intensifying cropping systems in the dry semiarid prairie by replacing summer fallow in crop rotations. In contrast, wheat grown on wheat stubble yielded only 66% of fallow-field yields, suggesting wheat is not as well suited for cropping on wheat stubble as the pulse crops. Water-use efficiency of dry pea on stubble was 107% of that on fallow, compared with 84% for chickpea and lentil and 81% for wheat.

Miller et al. (2002b) found grain yield for wheat was highest when grown on pulse crop stubbles, while grain yield for wheat grown on oilseed stubbles did not differ from yield of wheat grown on wheat stubble. Grain protein for wheat grown on both pulse and oilseed crop stubbles was higher than when grown on wheat stubble. Gan et al. (2003) found similar results for durum wheat grown on pulse and oilseed stubbles. Soil N contribution was increased markedly by pulse crop stubbles such that fertilizer N requirements for canola, mustard, and spring wheat grown on pulse stubble were reduced by an average of about 15 kg N ha^{-1}. Stubble related differences in soil available water did not affect the wheat test crop under the wetter-than-average conditions of this 5-yr trial at Swift Current, SK.

Cropping sequence benefits to cereal crops from broadleaf crops were observed only at sites with near-average growing season rainfall and not at sites experiencing severe drought (Miller and Holmes, 2005). Cropping sequence differences between wheat and flax or pea as the previous crop were not explained by soil water but were related to differences in soil N despite the use of high N fertilizer rates for the cereal test crops. Under average rainfall, cereal test crop yields following pea and chickpea ranged from 84 to 96% of the fallow control and were generally greater than that following wheat. Under severe drought, cereal test crop yields following pulse crops ranged from 21 to 41% of the fallow control and were equal or less than those following wheat.

Summarizing several years of crop sequencing research at Swift Current, SK, canola or mustard productivity was generally greater when grown on pea or lentil stubble compared with mustard and wheat stubble (Miller et al., 2003b). Under drier-than-normal conditions, pea yields were highest when grown on wheat stubble. Wheat productivity was least when grown on its own stubble. Pea and lentil provided rotational benefits to wheat, mustard, and canola and benefited most from being grown in wheat stubble, indicating a strong fit for diversified cropping systems on the semiarid northern Great Plains. Comparing across several crop sequencing research studies on the northern Great Plains, the yield increases have been attributed to increased conservation of soil water and/or soil N by inclusion of pulses within the cropping system.

CLIMATE CHANGE ON THE NORTHERN GREAT PLAINS

Historic Climate Trends

During the 20th century, temporal trends showing increases in temperature and precipitation across North America have supported the expected direction of climate change, as predicted by global climate models (GCMs) driven by an enhanced greenhouse gas effect. The GCMs predict the trend towards warming in the lower atmosphere that is generally more spatially coherent than that for increased precipitation. Although the enhanced greenhouse gas effect may not be the only factor involved in these trends, it is implicated as a key factor over the past few decades (Lean and Rind, 1998).

Temperature

The emerging trend towards global warming has been very striking over the 20th century in comparison to precipitation. On average, the temperature increase has been in the order of 0.4 to 0.8°C (Bonsal et al., 2001). The average increase in Canada has been 0.9°C (Zhang et al., 2000b) and in the United States 0.4°C (Karl et al. 1996); in general, North America has warmed 0.7°C (McCarthy et al., 2001).

There are spatial as well as temporal variations to the warming trends on the northern Great Plains. On the Canadian Prairies, between 1900 and 1998, Zhang et al. (2000b) found the annual mean daily maximum temperature (T_{mx}) increased generally $\leq$1.5°C, and significantly ($P < 0.05$) only in southern Saskatchewan.

However, the annual mean daily minimum temperature (T_{mn}) increase was larger (generally ≥1.5°C) and extended across the prairies. Seasonally, the greatest warming occurred during spring (March to May). Skinner and Gullet (1993) reported that for the prairie region between 1950 and 1989, annual T_{mx} and T_{mn} have increased by 1.7 and 1.1°C, respectively. At the same time, mean winter T_{mx} and T_{mn} have increased by 2.4 and 2.1°C, respectively, while warming in the spring has been even greater at 3.8 and 2.8°C, respectively. There appears to be seasonal trends in extreme temperatures as well. Lawson (2003) reported a decrease in extreme T_{mn} in January and February between 1914 and 1994 across the Canadian Prairie. Corresponding to this, Raddatz et al. (1991) indicate a shift in the coldest month from February to December in the eastern Prairies. These findings are supported by Bonsal et al. (2001), who suggest "Canada is not getting hotter, but rather less cold."

For the United States, Karl et al. (1996) stated that the daily minimum temperature increased about 10% more than the maximum. In addition, there has been a decrease in the day-to-day temperature variability (Karl et al. 1995). Between 1900 and 1994 over the northern Great Plains of the United States, Karl et al. (1996) found the annual average temperature (T_{mean}) increased by 1 to 3°C. The largest increase in T_{mean} occurred in North Dakota, with generally smaller increases occurring south and west of North Dakota.

Further evidence of a warming trend is the increase in length of the growing season. From 1950, spring temperatures over the northern Great Plains have increased between 1°C in the United States to over 3°C on the Canadian Prairies. In the northern Great Plains of the United States, last spring frosts occurred earlier and the frost-free season lengthened from 1948 to 1999 (Easterling, 2002). The average date of the last spring frost occurred earlier by 1.2 d per decade (6.2 d earlier in 1999 compared with 1948) and the frost-free season lengthened by 1.7 d per decade (8.8 d longer in 1999 than in 1948). For both Canada and the United States, there was little change in the first fall frost date during that same period. Over the later half of the 20th century, the general trend on the Canadian Prairie was for the mean last spring frost date to occur earlier by 2.4 d per decade and for the mean duration of the frost-free season to increase by 3.1 d per decade (Cutforth et al., 2004). The change in frost dates or frost-free duration was not uniform across the prairies (Cutforth et al., 2004; Shen et al., 2005). The largest trends for earlier last spring frost date and increasing frost-free season occurred in northern Alberta and the Peace River region of northern British Columbia whereas some of the smallest trends occurred over much of southern Alberta and southern Manitoba.

Over the past 100 yr, the gradual warming of the Canadian Prairies (Bootsma, 1994) has coincided with an increase in the frost-free period, an increase in the number of growing degree-days, and shifts in crop production regions. For example, "the area with sufficient CHU for corn production in Alberta, calculated according to the 1973 to 2002 climate normal, has extended northward by about 200 to 300 km, when compared with the 1913 to 1932 climate normal, and by about 50 to 100 km, when compared with the 1943 to 1972 climate normal" (Shen et al., 2005). Shen et al. (2005) suggest this expansion implies that the potential exists to grow crops in more northerly regions of Alberta than was possible in the past.

Coinciding with earlier warming has been a decrease in winter snowfall (with a large portion of the decrease falling as rain) in southern Saskatchewan and an earlier spring runoff on the northern Great Plains (Cutforth et al., 1999; Cayan et al., 2001). From 1955 to 1998, spring runoff for the Swift Current Creek drainage basin in southwestern Saskatchewan started earlier at an average rate of 0.55 d yr^{-1} (Cutforth et al., 1999). On average, in 1998, spring runoff from the drainage basin started 24 d earlier than in 1955.

Precipitation

The small global trend in precipitation has shown about a 1% increase over land. However, more evident has been the increase in precipitation over the 20th century during the cold months in the northern Hemisphere (Zhang et al., 2000b).

From 1900 to about 1998, the generally insignificant but positive precipitation trends in the Canadian Prairies (Zhang et al., 2000b) gradually changed to negative trends in the Northern Great Plains south of the Canada–United States border with the largest negative trends in Montana and Wyoming (Karl et al., 1996). The only positive trends in the northern Great Plains of the United States for precipitation totals were in South Dakota.

Excluding events with ≤0.5 mm precipitation, Akinremi et al. (1999) reported that for the Canadian Prairies between 1920 and 1995 there was a significant increase of 16 precipitation events within a year, mainly due to low-intensity events. However, during this period, the average amount of precipitation increased 0.62 mm each year. Between 1956 and 1995, there was an increase in rainfall of 16%, most of which was presumably due to the conversion of snowfall to rain in spring, coinciding with warmer and earlier springs (Akinremi et al., 2001).

From 1910 to 1996, Karl and Knight (1998) found annual precipitation amount averaged across the northern Great Plains of the United States increased slightly. Seasonally, precipitation totals increased for spring and summer and decreased for autumn and winter. The majority of the increase/decrease was accounted for by the trends of the highest class interval (the >90th percentile group). The frequency of precipitation events increased slightly on an annual basis, especially in the low to moderate precipitation class intervals. Precipitation events increased during spring and summer whereas events for autumn and winter were relatively unchanged. The proportion of total annual precipitation derived from heavy and extreme precipitation events has increased relative to more moderate precipitation events (Karl et al., 1995).

Future Climate

Forecasting climate relies on simulations of large-scale global climate models that respond to global forcing elements such as changes in greenhouse gas concentrations in the atmosphere. These models are run for a current equivalent CO_2 concentration in the atmosphere, and then for a doubling of concentration where the time for doubling is dependent on an emission scenario. The differences between these model runs for temperature and precipitation are then applied to the historic climate seasonal data to generate a future climate change scenario. Because of the very diverse outputs from individual global climate models, the Intergovernmental Panel on Climate Change recommends the use of more than one GCM for any assessment of climate impact and that the selected GCMs show a range of changes in the key climate variables, notably temperature and precipitation (Sauchyn et al., 2003).

"Most scientists agree that results of the model simulations are only indications of the potential trends in climate change conditions" (Kobiljski and Dencic, 2001). As new knowledge and understanding of climate processes are acquired, we need to assimilate this new information into climate models thereby continually updating predictions of future climates.

Temperature Change

The change forced by an enhanced greenhouse gas effect is predicted to cause global warming of 1.4 to 5.8°C by 2100 (Houghton et al., 2001). The predicted warming will not be spatially or temporally uniform and varies with the forecast model used. For a doubling of carbon dioxide concentration between 2040 and 2060, the Canadian Coupled Global Climate Model (CGCM1-A; Hengeveld, 2000) predicted that the Canadian prairies will warm by about 3.1°C (McGinn and Shepherd, 2003).

Rosenberg et al. (2003), using the HadCM2 GCM simulation for 2030, predicted temperature increases for the northern Great Plains region of the United States of <2.5°C by 2030 with increases in excess of 3°C by 2095.

Temporal and spatial patterns of temperature for the northern Great Plains were simulated using the Canadian GCM (CGCM2) and the UK GCM (HadCM3) (Fig. 2). By 2050, compared with the baseline (1961–1990) cli-

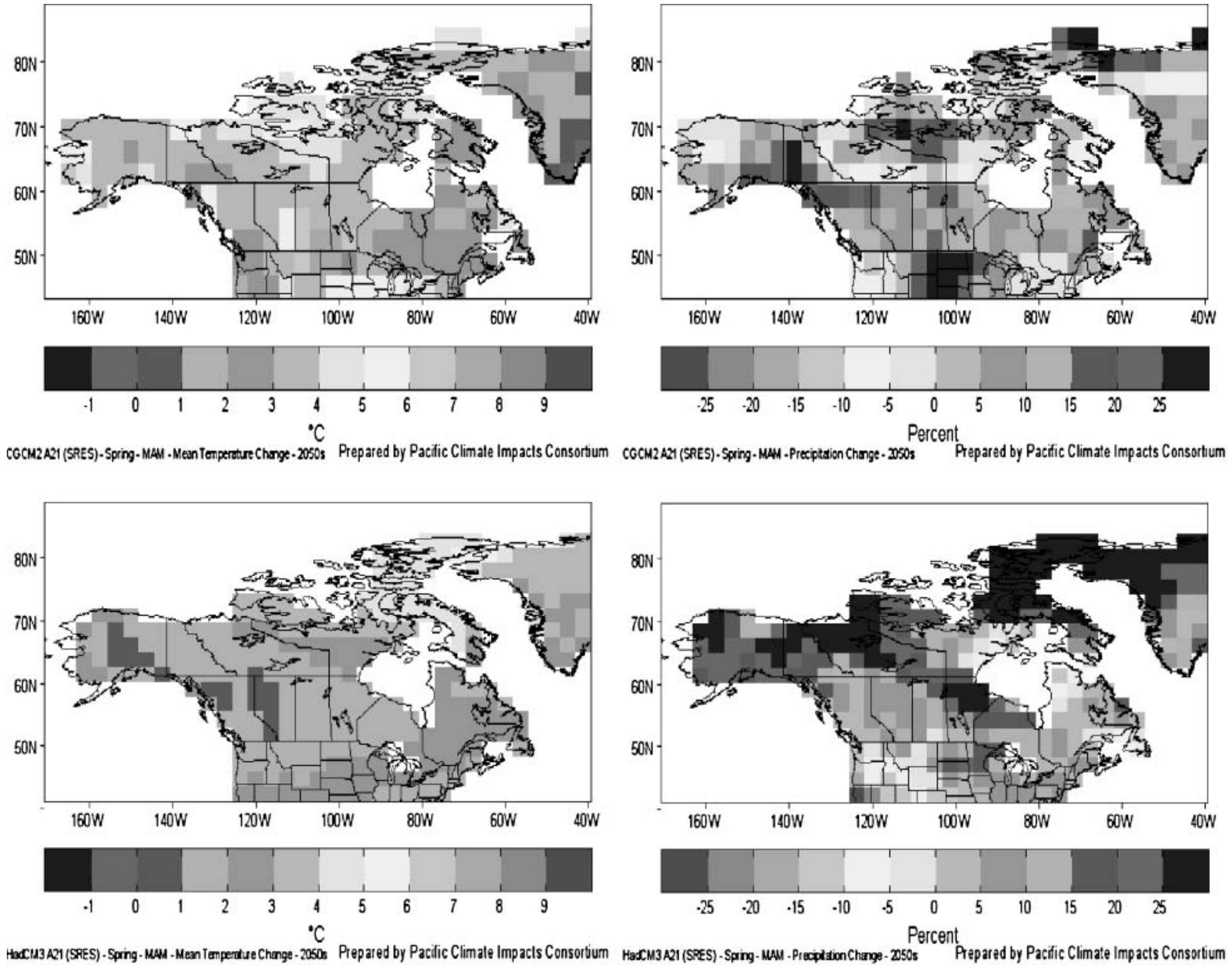

Fig. 2. Spring (March, April, May) temperature (left) and precipitation (right) predictions for 2050 by the Canadian (CGCM2) (top) and UK Hadley Centre (HadCM3) (bottom) global climate models. Predicted temperature (°C) and precipitation (%) changes are compared with the baseline period of 1961 to 1990 (obtained from www.pacificclimate.org/tools/select, verified 6 Sept. 2007). Image used with permission from the Pacific Climate Impacts Consortium.

mate, CGCM2 predicted increases in annual mean temperature of 2 to 5°C, whereas HadCM3 predicted temperature increases of 1 to 3°C, the larger temperature increases occurring over the U.S. Northern Plains. CGCM2 predicted spring (March, April, May) temperature increases of 3 to 9°C centered on North Dakota, whereas HadCM3 predicted smaller temperature increases of 1 to 3°C. CGCM2 predicted summer (June, July, August) temperature increases of 2 to 4°C, increasing in an west to east direction, while HadCM3 predicted temperature increases of 2 to 5°C, increasing in a north to south direction. There is generally good agreement between GCMs with the direction (increasing or decreasing) of temperature change, although the magnitude of change often differs.

Precipitation Change

One-third of the world's population is residing in water-stressed regions of the world (McCarthy et al., 2001). For them, understanding the impact of climate change on regional precipitation is crucial. For this reason, the downscaling of GCM output to regional scales has become a focus of the climate change modeling community. However, this goal is very difficult since forecasting the spatial and temporal pattern of precipitation amounts remains a highly uncertain science and can vary significantly among GCMs (Giorgi et al., 1994). The variation between GCMs for precipitation prediction is much greater than for temperature prediction. GCM precipitation predictions often disagree with respect to direction of change as well as the magnitude of change (Sauchyn et al., 2003).

Precipitation across the Canadian Prairies is predicted to increase by 4% annually, with Alberta receiving the greatest increase (Shepherd and McGinn, 2003; using CGCM1-A). Seasonal and spatial variations exist within this pattern. Most significant is that rainfall during the July to August period in southern Manitoba and southeastern Saskatchewan is predicted to decline by 30 mm.

In the United States, Giorgi et al. (1994) reported an average increase in precipitation in the cold and warm months of 21 and 16%, respectively, for a 2 × CO_2 scenario. For the central Plains, the increase for cold months was reported to be 19%, while for warm months the increase was 24%.

CGCM2 and HadCM3 predicted annual precipitation totals on the northern Great Plains for 2050 that changed little compared with the baseline (1961–1990) climate (Fig. 2). Seasonally, both CGCM2 and HadCM3 predicted spring precipitation to increase 5 to 15% on the Canadian Prairies. However, CGCM2 predicted a substantially greater spring precipitation increase (15 to >25%) over the northern Great Plains of the United States than HadCM3 (–5 to 25%). Both models predicted similar decreases (−15 to 0%) in summer precipitation; the change occurring in a northwest to southeast direction with the U.S. plains drier than the Canadian prairies.

Aridity

Sauchyn et al. (2002, 2003) developed aridity maps for the baseline time period (1961–1990) and for 2050 from temperature predictions by CGCM2 and HadCM3. For 1961 to 1990, they classified the driest region of the Canadian Prairies (southwest Saskatchewan to southeast Alberta) as dry subhumid (Fig. 3). The aridity index was determined by calculating potential ET using Thornthwaite's formula, which uses temperature as the sole measure of energy available for ET. By 2050, based on forecasts of temperature and precipitation, CGCM2 predicted a semiarid climate will develop in southwestern Saskatchewan and the dry subhumid area will expand substantially. By 2050, HadCM3 forecasted the least change in climate with the development of a small area of semiarid climate in southern Alberta and a slight increase in the area characterized by a dry subhumid climate. The differences between the model predictions arise chiefly because of the much larger temperature increases predicted by CGCM2.

Compared with the present climate, for doubled CO_2 climates, droughts could become more frequent and severe (Easterling et al., 2000; Lemmen and Warren, 2004; Motha and Baier, 2005).

PULSE RESPONSE TO FUTURE CLIMATES

Evidence suggests that the recent historic trends in climate have already forced changes in terrestrial ecosystem. Myneni et al. (1997) reported that spring time warming may be partially responsible for the increase in photosynthesis observed by satellite data in the mid to high latitudes. Evidence given by Andresen et al. (2001) for the Upper Great Lake states, suggested a relationship between increased total seasonal precipitation and decreased evaporation, and the average corn and soybean yield increase of 11.4 and 4.9 kg ha^{-1} yr^{-1}, respectively, over the past century. A more direct impact of elevated greenhouse gas concentrations is an increase in

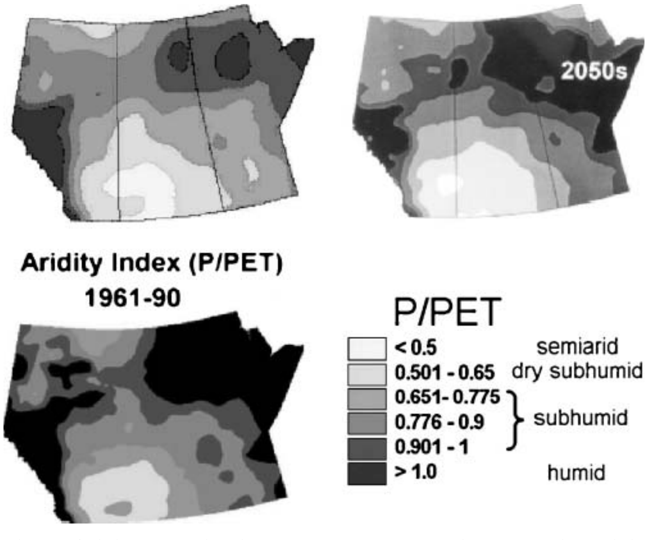

Fig. 3. Aridity scenarios for the 2050s based on forecasts of precipitation and temperature from the Canadian (CGCM2) (top left) and UK Hadley Centre (HadCM3) (top right) global climate models. These GCM experiments represent warm-dry and cool-wet scenarios, respectively. Aridity map for the Prairie Provinces (bottom left) for the baseline period 1961–1990 (from Sauchyn et al., 2002, 2003).

yield of temperate grasslands of 7.5 to 9% since preindustrial time (Jones, 1997).

Response to CO_2 Fertilization

Plants growing with increased CO_2 concentration exhibit increased rates of net photosynthesis and/or reduced stomatal diameter (Kobiljski and Dencic, 2001). "Partial stomatal closure leads to reduced transpiration per unit leaf area, and together with enhanced photosynthesis often improves WUE (Haskett et al., 2000). Consequently, increased CO_2 concentration can increase yield and reduce water use. Most crops grown in cool, temperate regions are C3 plants (including pulses) that respond positively to increased CO_2. Growth rates for these C3 crops can be increased by 10 to 50% in doubled CO_2 conditions" (Kobiljski and Dencic, 2001).

Under ambient CO_2, Allen et al. (2003) found large increases in soybean canopy ET as temperature and concomitant leaf to air vapor pressure deficit increased. Under doubled CO_2, canopy ET decreased 9% at 23°C but there was no CO_2 effect on ET when temperatures were 35°C or higher. "Canopy resistance (R_c) increased with increasing CO_2 concentration but decreased as air temperature increased. Water-use efficiency increased between 50 and 60% under doubled CO_2 at 28/18°C and at 40/30°C, but decreased with increasing temperature" (Allen et al., 2003). Simulation modeling showed that, in general, increases in atmospheric CO_2 concentration and precipitation have positive effects, while increasing temperature has a negative effect on crop production for semiarid climate conditions (Phillips et al., 1996; Yu et al., 2002). Further, higher atmospheric CO_2 concentration offsets the effects of climatic change. Compared with ambient CO_2 concentration, doubling CO_2 reduces the rate at which plant biomass decreases with increasing temperature and also reduces the rate at which plant biomass increases with increasing water availability. As well, the positive effect of CO_2 enrichment was larger under harsher (drier, warmer) climate conditions.

According to Allen et al. (2003), "if global warming occurs with rising CO_2, the small savings in ET associated with increasing R_c because of stomatal closure will be considerably offset by increases in ET driven by higher temperatures, which could increase the total amount of water required for crop production."

Simulated Response to Future Climates

Simulation models have been used to evaluate the impact of climate change on pulse production in the northern Great Plains. The severity of climate change effects on crop production depends on the size of the temperature increase. As previously noted, modeling indicates that increases up to 2.5°C cause variable effects on the agricultural sector, with improvements in many cases, particularly in temperate climate regions; however, temperature increases above 2.5°C are generally projected to have negative overall effects (Intergovernmental Panel on Climate Change, 2001; Smith and Almaraz, 2004). Laurila (2001) reported that higher air temperature can reduce the maturity time of spring wheat and result in a yield loss of 20%. Combining higher CO_2 concentrations with higher temperatures, the yield increase was reduced from 142% (elevated CO_2) to 106%. The impact of earlier seeding dates reduced the negative impact of higher temperatures, and improved the associated yield increases to 178% of the baseline yield. In addition to avoiding higher temperatures and fast maturity rates that can decrease yields, earlier seeding dates of short season crops would presumably enable crops to avoid late-season drought (McGinn and Shepherd, 2003).

Simulation studies suggest soybean yields on the U.S. northern Great Plains will respond more adversely to predicted future climates than winter wheat yields (Izaurralde et al., 2003; Thomson et al., 2005). Whether the GCM used to predict future climates favored a warm and dry scenario or a cool and wet scenario, simulated yields for both soybean and winter wheat increased as CO_2 concentration increased from 365 to 560 ppm (Table 2). Izaurralde et al. (2003) found simulated yields for winter wheat either did not change or increased for future climate predicted by the Hadley model (cooler, wetter scenario), whereas simulated soybean yields did not change or decreased (Table 2). For each crop, the yield response was location-dependent, reflecting regionalization of predicted climate change. Thomson et al. (2005) found the response of winter wheat yields to climate change was somewhat independent of temperature but dependent on CO_2 concentration. Whether the predicted temperature increase was mild or severe, the percentage change (compared with the baseline climate) in winter wheat yield tended to decrease slightly (i.e., reduced yields) with no CO_2 fertilization, but increased between 10 and 20% with CO_2 fertilization. Simulated soybean yields were more adversely responsive to temperature increase than were simulated winter wheat yields. Generally, simulated

Table 2. Simulated soybean and winter wheat yields for the Mountain and Northern Plains regions (that approximate the western and eastern portions of the northern Great Plains of the United States) (from Izaurralde et al., 2003).

	Grain yield			
	Wheat		Soybean	
CO_2/scenario†	Mountain	Northern Plains	Mountain	Northern Plains
	$Mg\ ha^{-1}$			
	Main effect means			
365	2.00 b‡	3.06 b	0.44 b	1.25 b
560	2.68 a	3.93 a	0.60 a	1.60 a
Baseline	2.14 b	3.40 ab	0.57 a	1.71 a
Had2030	2.06 b	3.37 b	0.43 b	1.27 b
Had2095	2.81 a	3.71 a	0.55 a	1.29 b
	Treatment means			
Baseline-365	1.84 c	3.09 c	0.49 bc	1.52 b
Had2030-365	1.74 c	2.90 c	0.36 c	1.10 c
Had2090-365	2.42 b	3.20 c	0.46 bc	1.12 c
Baseline-560	2.44 b	3.71 b	0.66 a	1.90 a
Had2030-560	2.38 b	3.85 ab	0.50 b	1.45 b
Had2090-560	3.21 a	4.21 a	0.64 a	1.46 b

† Main effect means are for climate scenarios: Baseline (1961–1990), HadCM2 projections for 2030 (Had2030) and 2095 (Had2095) averaged across CO_2 concentrations. CO_2 scenarios: 365 and 560 ppm averaged across climate. Treatment means include climate-CO_2 scenario combinations.

‡ Means within a column followed by different letters are significantly different at $P = 0.1$.

soybean yields decreased in response to future climate scenarios; the reduction in yield was moderated somewhat by CO_2 fertilization to the extent that soybean yields increased slightly for milder temperature increases combined with CO_2 fertilization (Thomson et al., 2005).

The soybean production area on the northern Great Plains will change as climate changes, and the area and location of the changes depended upon the scenarios chosen to predict future climates (Thomson et al., 2005). Under cool and wet scenarios with or without CO_2 fertilization, soybean production area increased by 5 to 15%; whereas under warm and dry scenarios, the soybean production area remained relatively unchanged except for a reduction in area when predicted warming was severe with no CO_2 fertilization (Thomson et al., 2005). On the other hand, changes to the winter wheat production area on the northern Great Plains were insignificant under all scenarios. Smith and Almaraz (2004) conclude that climate change will result in northward migration of crop production, especially on the Canadian Prairies as northern areas become warmer for annual crop production.

ADAPTATION TECHNOLOGIES AND CLIMATE CHANGE

Aridity is expected to remain relatively unchanged or increase (i.e., climate will impose a greater stress on crops) under climate change in the northern Great Plains. Thus, to maintain agricultural viability in a climate with increasing aridity, there is a need for technologies that increase the water-use-efficiency of crops and cropping systems. Superimposed on climate change are trends in climate that cause climate normals to shift in one direction (i.e., warming, increased aridity) such that climate is no longer oscillating about a stationary average. As climate shifts, the synchrony between climate and plants commonly grown in the northern Great Plains is disrupted. These plants experience more stress as climatic parameters such as temperature and precipitation occur more often outside their coping range. Adaptation technologies are attempts to restore the synchrony or to establish new synchronization between climate and plant communities. Continued research into the adaptive capabilities of current agricultural technologies and the development of future technologies will contribute to maximizing crop production in the future (Dhungana et al., 2006). Adaptive technologies to the northern Great Plains include the following: changing seasonality of production, changing sowing date, choice of crop varieties or species, development of new varieties, improving water supply and irrigation systems including efficiency in use, changing tillage practices, and diversifying the farm enterprise (Smit and Skinner, 2002; Bradshaw et al., 2004; Burton and Lim, 2005).

Research Needs: Pulse Crop Adaptation to Climate Change

Cultivar Development

Developing new agronomic technologies will require prediction of future climatic conditions that are likely to occur. Developing new cultivars will require identification of crop traits that will allow the crop to respond well in the future climate. Coupling crop and climate simulation models will increase our understanding of the types of cultivars and the management practices necessary to optimize agriculture in the future (Dhungana et al., 2006).

Global warming is predicted to extend the growing season in the northern Great Plains through earlier springs and later falls (McGinn and Shepherd, 2003; Motha and Baier, 2005). “It will be possible to grow crop cultivars with longer times to maturity and, therefore, greater yield potentials in much of the temperate zones” (Smith and Almaraz, 2004). The high yield potential may be tempered by exposure to increased temperatures during the bloom period and seed fill that may adversely impact seed set and overall yield. Current pulse production is based predominantly on spring-sown cultivars and the emphasis in breeding is to select for earliness to flower and mature (Berger et al., 2004; Turner et al., 2005). In a changing climate, these breeding objectives are expected to remain valid especially if aridity is maintained or increased. For the segment of environments where extended periods of crop growth are possible, breeding objectives may need to be adjusted to accommodate specific yield potentials (Berger et al., 2006). Further, with increased warming and longer growing seasons, the climate of the northern Great Plains will become more favorable for the production of warm-season pulses such as dry bean and soybean. Breeding efforts can accelerate the adaptation of and contribute to the rapid expansion of the area suitable for warm-season pulse production on the northern Great Plains.

Availability of cold-tolerant, winter-hardy germplasm of both pea and lentil that allow the crop to be sown in the fall and survive the winter may provide additional options for production of pea and lentil as the traditionally cold northern Great Plains environments become milder. Specific advantages of fall-sown pea and lentil will depend largely on whether a warm and dry or a cool and wet scenario is the ultimate outcome. However, it is expected that a continuum of environments will characterize future production regions much the same as is experienced in current production regions.

Winter pea and lentil have been shown to survive temperatures as low as −9 to −12°C (Swenson and Murray, 1983). Advantages of pulse crop establishment in the fall include (i) the ability to establish the crop in warmer and drier field conditions, avoiding the risk of poor seedling establishment in the spring or limited field access in the spring due to cold, wet soil conditions; (ii) allowing a more manageable volume of field operations between the fall and spring; and (iii) maintain an increased yield potential through more efficient use of precipitation and avoidance of severe summer temperatures through early maturity.

Chickpea and lentil are susceptible to a number of foliar pathogens, which have increased prevalence during high-rainfall seasons (Martens et al., 1984; Miller et al., 2002a). Pulse industry sources in Australia, Canada, and the United States consider climatic conditions that are favorable for the development of ascochyta blight [*Ascochyta rabiei* (Pass.) Lab.] to be the key factors limiting adaptation of chickpea (Wiese et al., 1995). As a result, chickpea may be considered best adapted to semiarid environments of the southern and western regions of the northern Great Plains, where climatic conditions are least favorable for the development of ascochyta blight (Miller et al., 2002a). Similar to chickpea, both lentil and pea are expected to encounter increased pressure from foliar pathogens in environments with increased precipitation. Combination of genetic resistance and appropriate agronomic control practices, such as adjusting sowing time to avoid disease development, will provide the greatest potential for crop success in a changing climate.

Incorporation of winter pea and lentil in production systems will surely expose these crops to increased disease pressure from an expanded spectrum of pathogens. Most important will be the foliar fungal pathogens, *Mycosphaerella pinodes* (Berk. and Bloxam) Vestergr., *Phoma medicaginis* var. pinodella (L.K. Jones). These pathogens are favored by cool and wet conditions which typify the early spring. Additional disease pressure may be experienced from soilborne pathogens *Sclerotinia sclerotiorum* (Lib.) de Bary., *Aphanomyces euteiches* (Drechs.), and *Fusarium solani* (Mart.) f. sp. *pisi* (F.R. Jones) (W.C. Snyder and H.N. Hans). Genetic resistance to all these pathogens is available in current germplasm collections; however, in all cases it is partial and heavily influenced by environmental conditions, making breeding and selection for resistance more difficult. Increasing the level of disease resistance in all legume crops grown in the northern Great Plains region will continue to be a primary objective of plant breeding.

Cultivar Assessment: Relative Adaptability to Climate Change

There are large genotypic differences in the tolerance of pulses to drought (Anbessa and Bejiga, 2002). It appears that reduced water loss from the plant and extensive extraction of soil moisture are factors involved in the adaptation of chickpea to drought conditions. Drought escape is an important phenological characteristic at sites with terminal drought (Berger et al., 2004; Turner et al., 2005). High-yielding genotypes generally flower early, pod early, and have a relatively long flowering period. However, at sites where drought is severe throughout the growth period, high-yielding genotypes have a high degree of biomass translocation from leaves to stems to pods. Berger et al. (2004) suggest that, depending on the type of water stress, physiological mechanisms and/or phenological development play a role in the adaptation of chickpea (pulses) to water-limited environments. Also, lentil and chickpea have considerable potential for drought resistance through osmotic adjustment (Leport et al., 1998; Turner et al., 2001, 2005). Therefore, a number of mechanisms are employed by plants to survive drought conditions.

Significant variation for seed yield in response to elevated CO_2 has been observed among soybean cultivars (Ziska et al., 1998). Although all cultivars show significant increase in seed yield with increased CO_2, there is considerable variation in yield enhancement, ranging from 35 to 80% (Ziska and Bunce, 2000; Ziska et al., 2001). "The sensitivity of seed yield response to CO_2 is associated with plasticity in the ability to form new seed in axillary branches in a high CO_2 environment" (Ziska et al., 2001). Screening of soybean germplasm may be an effective strategy to begin selecting soybean lines that will maximize yield in future environments with higher CO_2 (Ziska and Bunce, 2000).

Research Needs: Cropping Systems and Climate Change

Irrigation

A large proportion of the irrigated agriculture on the western portion of the northern Great Plains is based on the many small rivers that run out of the Rocky Mountains and onto the plains (Motha and Baier, 2005). River flows rely heavily on melt from winter snow pack and from glaciers in the Rocky Mountains. As winter temperatures continue to warm, the snow pack will be reduced because of increased melt during winter and because more precipitation will fall as rain rather than snow (Cutforth et al., 1999; Motha and Baier, 2005). As well, because of increasing winter temperatures, many of these glaciers, especially in the Canadian Rocky Mountains, will continue to shrink. For instance, the Peyto glacier in Alberta has lost 70% of its mass during the last few decades. In response to decreased river flows because of reduced melt, especially on the western half of the northern Great Plains, irrigation use will continue to decrease in the future (Smith and Almaraz, 2004). This has already occurred on the western Canadian Plains where, since 1950, less water has been flowing into rivers, lowering the availability of water for crop irrigation (Demuth and Pietroniro, 2003). "Urban populations will continue to increase, and competition between urban and agricultural uses of water will intensify" (Motha and Baier, 2005). As irrigation water becomes less available, production agriculture will be forced to rely more heavily on crops adapted to dryland production. Pea, lentil, and chickpea are particularly well adapted to dryland production and can be expected to play a key role in crop rotations in increasingly arid environments.

Agronomy

Global warming will promote earlier springs that will prompt management changes such as earlier seeding (Smith and Almaraz, 2004). Under a doubled CO_2 climate scenario, seeding dates in western Canada are projected to advance by approximately 3 wk (Motha and Baier, 2005).

Producers on the semiarid Canadian prairies are faced with several major limitations to cereal production, including a lack of water and soil erosion by wind. As well, several GCMs predict aridity will increase in severity throughout the 21st century. Further, damaging winds may also increase in severity and occurrence in response to future climate change on the northern Great Plains

(Wheaton, 1990). These limitations can be addressed by employing no-till practices. Stubble is left intact and standing to protect the soil from the wind (Siddoway, 1970) and to increase snow catchment and thereby soil water reserves through snow melt infiltration (Campbell et al., 1992a; Steppuhn, 1994). Not only are yields increased through the additional stored soil water, but standing stubble may also alter the microclimate to provide less stressful environmental conditions for plant growth (Campbell et al., 1992a; Cutforth and McConkey, 1997). The milder microclimate associated with stubble can also favor production of fall-sown legume crops through protection from cold temperatures and desiccating winds.

In semiarid climates, appropriate management of the previous crop stubble in combination with seeding method is important to improve growing conditions for the subsequent pulse crop (Cutforth et al., 2002). Standing stubble changes the microclimate near the soil surface by reducing soil temperatures, solar radiation, wind speed, and potential ET (Table 3) (Cutforth and McConkey, 1997; Cutforth et al., 2002; Nielsen et al., 2005). The microclimate effects are dependent upon stubble height and are much more pronounced for tall (0.3m) versus short (0.15 m) stubble. Pulse crops (chickpea, field pea, lentil) respond similarly and positively to the altered microclimate (Table 4). On average, in a semiarid environment, tall and short stubble increase grain yield by about 13 and 4% compared with cultivated stubble. Crop water use is generally not affected by stubble height, so the increased grain production is due to increased WUE (Cutforth et al., 2002). Therefore, tall and short stubble increase the average WUE by about 16 and 8%, respectively, compared with cultivated stubble. Seeding pulses into taller standing stubble tends to raise the height of the plant and the basal pods (Cutforth et al., 2002). There are three likely reasons for this: (i) natural trellising on the stubble, (ii) natural elongation response to growing in the partial shade produced by the standing stubble, and (iii) more vigorous growth due to better water conservation (Miller et al., 2002a). Thus, direct seeding into tall cereal stubble can improve harvestability, thereby expanding the effective area of suitable soil landscapes for pulse production (Miller et al., 2002a).

Soil erosion is a perennial concern in the northern Great Plains with conventional tillage-based systems, and when pulse crops are introduced into the cropping system, the lower residue production combined with rapid residue decomposition can make for disastrous situations (Miller et al., 2002a). Consequently, soil landscapes that are prone to erosion from wind or water may not have sufficient residue after a pulse crop to prevent excessive soil erosion if that residue is tilled. No-till practices that maximize conservation of the pulse residue and carryover residue from previous crops are necessary for sustainable production of pulse crops on highly erodible soil landscapes (Miller et al., 2002a).

Table 3. Daily average wind speed and air temperature 15 cm above the soil surface, evaporation at the soil surface, and daily average soil temperature 5 cm below the soil surface before flowering of pulses grown in cultivated, short and tall stubble at Swift Current, SK. Wind speed and evaporation were averaged across 1996–1998, whereas temperatures were averaged across 1996–1998 and 2000 (data from Cutforth et al., 2002).

Stubble height†	Wind	Temperature		Evaporation
		Air	Soil	
	$m\ s^{-1}$	°C		g water h^{-1}
Cultivated	1.7 a	12.4 a	15.2 a	3.17 a
Short (15 cm)	1.3 b	13.8 a	14.6 ab	2.85 b
Tall (30 cm)	0.5 c	14.1 a	14.4 b	2.34 c

† Letters indicate significant differences (Tukey) between stubble height treatments at $P < 0.10$.

Table 4. Effects of stubble height on vine length, plant height, grain yield, evapotranspiration (ET), and mean water use efficiency (WUE) for pulses grown in 1996–1998 and 2000 in the semiarid prairie at Swift Current, SK. Multiple means comparisons were made using the Tukey procedure at $P < 0.10$ (data from Cutforth et al., 2002).

Stubble height	Vine length	Plant height	Grain yield	ET	WUE
	cm		$kg\ ha^{-1}$	mm	$kg\ ha^{-1}\ mm^{-1}$
Cultivated	46.8	36.7	1782	246	7.49
Short	49.3	37	1858	242	8.06
Tall	53.2	40.8	2008	240	8.70
Tukey	4.6	NS	161	NS	0.95

In wetter regions, no-till systems slow the increase of early season soil temperature, and therefore, negatively affect seed germination, seedling emergence, and final stand establishment, even though this has only a small impact on final crop yield (Hayhoe et al., 1999). In the northern Great Plains state of Montana, Chen et al. (2006) found that winter lentil yields generally increased as stubble height increased. However, for one unusually cool period of emergence and seedling development, the seed yield of winter lentil was reduced by taller (35-cm) compared with shorter (10-cm) stubble. In the heat-limited environment, lentils may have benefited from the earlier soil warming associated with the shorter stubble in early spring.

Crop Sequencing and Rotations

Rotational benefits of pulse crops are expected to play a critical role in intensifying crop production systems in the future. Rotational benefits of pulse crops for wheat and barley production include enhanced soil fertility, increased WUE, as well as decreased losses in yield and quality from weeds and soilborne disease (Derksen et al., 2002; Krupinsky et al., 2002). The rotational benefits of including pulses in cropping systems, especially in the Canadian semiarid prairies, are at least partially due to the combined effects of increased soil N supply and increased soil water conservation positively affecting other crops within the rotation (Miller et al., 1998; Angadi et al., 1999; Miller et al., 2002a, 2002b; Gan et al., 2003; Miller and Holmes, 2005). During a long-term crop rotation study at Swift Current, Campbell et al. (1992b) and Zentner et al. (2001) reported that a continuous crop rotation of lentil alternating every other year with wheat was more profitable than any other rotation in the study.

Rotational benefits from pulse crops, including the winter pulse crops, can be obtained in both semiarid and subhumid regions, but the knowledge for describing the underlying causes of rotational effects remains incomplete. Continued research into cropping system design will likely become increasingly important for the economic sustainability and viability of grain production in the northern Great Plains, especially in light of the potentially harsher climates predicted for the future. Enhanced understanding of how pulse crops influence yield and quality of succeeding crops would allow producers to alter management to capitalize on beneficial effects while minimizing negative impacts (Miller et al., 2002a).

SUMMARY

There is general consensus that global warming will continue over the next 50 to 100 yr. Global climate models and crop simulation models are valuable tools for studying the effect of predicted climate change on regional crop production. However, regional crop production under future climates is dependent upon the accuracy of these scenarios which often result in one of two contrasting outcomes, an increasingly warm and dry or increasingly cool and wet climate. Consideration of CO_2 fertilization and adaptation of crop management (e.g., seeding date, varieties) often result in enormous variation in predicted crop production (Reilly et al., 2003; Edmonds and Rosenberg, 2005). The overall impact of these changes on crops will depend on a combination of factors, including crop species response to CO_2 enrichment, regional change in precipitation and water availability, growing season temperature impact on maturity rates, and adaptive shift in seeding dates that impact both temperature and available water for growth. Other factors may emerge to limit any potential yield increases, such as soil fertility and the impact of shifts in weed, insect, and disease populations. Pulse crops are quite plastic in their growth habit and are able to adapt to a variety of environmental conditions. Significant genetic variation for plant growth characters and specific adaptation is available in germplasm collections and is available for crop improvement. Adjustments in breeding objectives and shifts in crop management will likely be slow due to uncertainty surrounding the direction and degree of change, but awareness of the likelihood for climate change will allow plant breeders to make adjustments and selections more quickly. Despite uncertainties surrounding climate change across the northern Great Plains, significant evidence is mounting in support of imminent change and production agriculture as a whole must be prepared to adjust.

Briefly, adaptative technologies for the northern Great Plains include the following:

Developing chickpea, lentil, and pea cultivars resistant to foliar blights
Developing winter pulses to avoid summer heat/drought
Developing determinant cultivars of chickpea and lentil that will be less affected by cool and wet falls
Developing chickpea and lentil cultivars with earlier phenology to escape terminal droughts (i.e., able to mature before onset of drought)
Developing warm-season pulses such as dry bean and soybean adapted to the warming climate and longer growing seasons
Identifying cultivars that have increased heat/water stress tolerance
Identifying cultivars that have higher yield response to increased CO_2
Developing irrigation practices for increased WUE
Earlier seeding in response to earlier springs
Developing and promoting seeding practices that alter microclimate in and above the crop canopy, thereby increasing crop yields and/or water use efficiencies
Developing and promoting seeding and residue management practices that conserve water and soil
Extending crop rotations by substituting pulse crops for fallow
Determining the crop sequencing within cropping rotations that optimizes yields and water use efficiencies of crops and cropping systems

ACKNOWLEDGMENTS

We extend our thanks to the anonymous reviewers, and to Dr. Perry Miller and Dr. George Clayton whose comments and suggestions contributed to the completion of this review.

REFERENCES

Akinremi, O.O., S.M. McGinn, and H.W. Cutforth. 1999. Precipitation trends on the Canadian Prairies. J. Clim. 12:2996–3003.

Akinremi, O.O., S.M. McGinn, and H.W. Cutforth. 2001. Seasonal and spatial patterns of rainfall trends on the Canadian prairies. J. Clim. 14:2177–2182.

Allen, L.H., Jr., D. Pan, K.J. Boote, N.B. Pickering, and J.W. Jones. 2003. Carbon dioxide and temperature effects on evapotranspiration and water use efficiency of soybean. Agron. J. 95:1071–1081.

Anbessa, Y., and G. Bejiga. 2002. Evaluation of Ethiopian chickpea landraces for tolerance to drought. Genetic Res. Crop Evol. 49:557–564.

Andresen, J.A., G. Alagarswamy, C.A. Rotz, J.T. Ritchie, and A.W. LeBaron. 2001. Weather impacts on maize, soybean, and alfalfa production in the Great lakes Region, 1895–1996. Agron. J. 93: 1059–1070.

Angadi, S., B. McConkey, D. Ulrich, H. Cutforth, P. Miller, M. Entz, S. Brandt, and K. Volkmar. 1999. Developing viable cropping options for the semiarid prairies. Project Rep. Agric. Agri-Food Canada, Swift Current, SK.

Angadi, S.V., Y. Gan, P.R. Miller, B.G. McConkey, R.P. Zentner, and C.L. McDonald. 2003. Water use and water use efficiency of field pea and chickpea under the semiarid Canadian Prairie conditions. *In* Proc, Soils and Crops Workshop [CD-ROM]. 17–18 Feb. 2003. Univ. of Saskatchewan, Saskatoon.

Berger, J.D., N.C. Turner, K.H.M. Siddique, E.J. Knights, R.B. Brinsmead, I. Mock, C. Edmonson, and T.N. Khan. 2004. Genotype by environment studies across Australia reveal the importance of phenology for chickpea (*Cicer arietinum* L.) improvement. Aust. J. Agric. Res. 55:1071–1084.

Berger, J.D., M. Ali, P.S. Basu, B.D. Chaudhary, S.K. Chaturvedi, et al. 2006. Genotype by environment studies demonstrate the critical role of phenology in adaptation of chickpea *(Cicer arietinum* L.) to high and low yielding environments of India. Field Crops Res. 98:230–244.

Bonsal, B.R., X. Zhang, L.A. Vincent, and W.D. Hogg. 2001. Characteristics of daily and extreme temperatures over Canada. J. Clim. 14:1959–1976.

Bootsma, A. 1994. Long term (100 yr) climatic trends for agriculture at selected locations in Canada. Clim. Change 26:65–88.

Borstlap, S., and M.H. Entz. 1994. Zero-tillage influence on canola, field pea, and wheat in a dry subhumid region: Agronomic and physiological responses. Can. J. Plant Sci. 74:411–420.

Bradshaw, B., H. Dolan, and B. Smit. 2004. Farm-level adaptation to climate variability and change: Crop diversification in the Canadian Prairies. Clim. Change 67:119–141.

Brevedan, R.E., and D.B. Egli. 2003. Short periods of water stress during seed filling, leaf senescence, and yield of soybean. Crop Sci. 43(6):2083–2088.

Burton, I., and B. Lim. 2005. Achieving adequate adaptation in agriculture. Clim. Change 70:191–200.

Campbell, C.A., B.G. McConkey, R.P. Zentner, F. Selles, and F.B. Dyck. 1992a. Benefits of wheat stubble strips for conserving snow in southwestern Saskatchewan. J. Soil Water Conserv. 47:112–115.

Campbell, C.A., R.P. Zentner, F. Selles, V.O. Biederbeck, and A.J. Leyshon. 1992b. Comparative effects of grain lentil-wheat and monoculture wheat on crop production, N economy, and N fertility in a Brown Chernozem. Can. J. Soil Sci. 72:1091–1107.

Cayan, D.R., S.A. Kammerdiener, M.D. Dettinger, J.M. Caprio, and D.H. Peterson. 2001. Changes in the onset of spring in the western United States. Bull. Am. Meteorol. Soc. 82(3):399–415.

Chen, C., P. Miller, F.J. Muehlbauer, K. Neill, D. Wichman, and K.E. McPhee. 2006. Winter pea and lentil response to seeding date and micro- and macro-environments. Agron. J. 98:1655–1663.

Cutforth, H.W., and B.G. McConkey. 1997. Stubble height effects on microclimate, yield and water use efficiency of spring wheat grown in a semiarid climate on the Canadian Prairies. Can. J. Plant Sci. 77:359–366.

Cutforth, H.W., B.G. McConkey, R.J. Woodvine, D.G. Smith, P.G. Jefferson, and O.O. Akinremi. 1999. Climate change in the semiarid prairie of southwestern Saskatchewan: Late winter-early spring. Can. J. Plant Sci. 79:343–350.

Cutforth, H.W., B.G. McConkey, D. Ulrich, P.R. Miller, and S.V. Angadi. 2002. Yield and water use efficiency of pulses seeded directly into standing stubble in the semiarid Canadian prairie. Can. J. Plant Sci. 82:681–686.

Cutforth, H.W., E.G. O'Brien, J. Tuchelt, and R. Rickwood. 2004. Long-term changes in the frost-free season on the Canadian Prairies. Can. J. Plant Sci. 84:1085–1091.

Demuth, M.N., and A. Pietroniro. 2003. The impact of climate change on the glaciers of the Canadian Rocky Mountain eastern slopes and implications for water resource-related adaptation in the Canadian prairies: Phase I, Headwaters of the North Saskatchewan River basin. CCAF-PARC Project P55. Available at www.parc.ca/pdf/research_publications/water1.pdf [verified 31 Aug. 2007]. Prairie Adaption Research Collaborative, Regina, SK, Canada.

Derksen, D.A., R.L. Anderson, R.E. Blackshaw, and B. Maxwell. 2002. Weed dynamics and management strategies for cropping systems in the Northern Great Plains. Agron. J. 94:174–185.

Dhungana, P., K.M. Eskridge, A. Weiss, and P.S. Baenziger. 2006. Designing crop technology for a future climate: An example using response surface methodology and the CERES-Wheat model. Agric. Syst. 87:63–79.

Easterling, D.R., T.R. Karl, K.P. Gallo, D.A. Robinson, K.E. Trenberth, and A. Dai. 2000. Observed climate variability and change of relevance to the biosphere. J. Geophys. Res. 105:20,101–20,114.

Easterling, D.R. 2002. Recent changes in frost days and the frost-free season in the United States. Bull. Am. Meteor. Soc. 83(9):1327–1332.

Edmonds, J.A., and N.J. Rosenberg. 2005. Climate change impacts for the conterminous USA: an integrated assessment summary. Clim. Change 69:151–162.

Erskine, W., M. Tufail, A. Russell, M.C. Tyagi, M.M. Rahman, and M.C. Saxena. 1994. Current and future strategies in breeding lentil for resistance to biotic and abiotic stresses. Euphytica 73:127–135.

Gan, Y., P.R. Miller, P.H. Liu, F.C. Stevenson, and C.L. McDonald. 2002. Seedling emergence, pod development, and seed yields of chickpea and dry pea in a semiarid environment. Can. J. Plant Sci. 82:531–537.

Gan, Y.T., P.R. Miller, B.G. McConkey, R.P. Zentner, F.C. Stevenson, and C.L. McDonald. 2003. Influence of diverse cropping sequences on durum wheat yield and protein in the semiarid Northern Great Plains. Agron. J. 95:245–252.

Giorgi, F., C.S. Brodeur, and G.T. Bates. 1994. Regional climate change scenarios for the United States produced with a nested regional climate model. J. Clim. 7:375–399.

Harris, H.C. 1979. Some aspects of agroclimatology of West Asia and North Africa. p. 7–14. *In* G.C. Hawtin and G.J. Chancellor (ed.) Food legume improvement and development. Int. Dev. Res. Cent., Ottawa, ON, Canada.

Hawthorne, W., J. Hannay, and D. Heinjus. 2003. Growing chickpeas. Available at http://www.pir.sa.gov.au/__data/assets/pdf_file/0007/37645/Growing_Chickpeas.pdf [updated Aug. 2003; verified 31 Aug. 2007]. Gov. of South Australia, Dep. of Primary Industries and Resources.

Haskett, J.D., Y.A. Pachepsky, and B. Acock. 2000. Effect of climate and atmospheric change on soybean water stress: a study of Iowa. Ecol. Modell. 135:265–277.

Hayhoe, K., A. Jain, H. Pitcher, C. MacCracken, M. Gibbs, D. Wuebbles, R. Harvey, and D. Kruger. 1999. Costs of multigreenhouse gas reduction targets for the USA. Science 29:905–906.

Hengeveld, H.G. 2000. Projections for Canada's climate future. Science Assessment and Integration Branch Report. Minister of Public Works and Government Service, Canada.

Hnatowich, G. 2000. Pulse production manual 2000. Available at: www.saskpulse.com/media/pdfs/ppm-entire-manual.pdf [verified 31 Aug. 2007]. Saskatchewan Pulse Growers, Saskatoon, SK, Canada.

Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. Van der Linden, X. Dai, K. Maskell, and C.A. Johnson (ed.) 2001. Climate Change 2001: The scientific basis. Contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Intergovernmental Panel on Climate Change. 2001. Climate Change 2001: Synthesis Report, Summary for Policymakers. Available at www.ipcc.ch/pub/un/syreng/spm.pdf [verified 31 Aug. 2007]. IPCC, Geneva.

Izaurralde, R.C., N.J. Rosenberg, R.A. Brown, and A.M. Thomson. 2003. Integrated assessment of Hadley Center (HadCM2) climate-change impacts on agricultural productivity and irrigation water supply in the conterminous United States. Part II. Regional agricultural production in 2030 and 2095. Agric. For. Meteorol. 117:97–122.

Johnston, A., P. Miller, and B. McConkey. 1999. Conservation tillage and pulse crop production-western Canada experiences. p. 176–182. *In* Momentum in northwest direct seed farming. Proc. Northwest Direct Seed Cropping Syst. Conf., Spokane, WA. 5–7 Jan.1999. Univ. of Idaho, Moscow.

Johnston, A.M., G.W. Clayton, G.P. Lafond, K.N. Harker, T.J. Hogg, E.N. Johnson, W.E. May, and J.T. McConnell. 2002. Field pea seeding management. Can. J. Plant Sci. 82:639–644.

Jones, M.B. 1997. The impacts of global climate change on grassland ecosystems. p. 1,810,188. *In* J.G. Buchanan-Smith (ed.) Proc. Int. Grassl. Congr., 18th, Winnipeg, MB, and Saskatoon, SK, Canada. 8–19 June 1997. Grasslands 2000, Winnipeg, MB, Canada.

Karl, T.R., R.W. Knight, and N. Plummer. 1995. Trends in high-frequency climate variability in the twentieth century. Nature 377: 217–220.

Karl, T.R., R.W. Knight, D.R. Easterling, and R.G. Quayle. 1996. Indices of climate change for the United States. Bull. Am. Meteor. Soc. 77:279–292.

Karl, T.R., N. Nicholls, and J. Gregory. 1997. The coming climate. Sci. Am. 276:78–83.

Karl, T.R., and R.W. Knight. 1998. Secular trends of precipitation amount, frequency, and intensity in the USA. Bull. Am. Meteor. Soc. 79(2):231–241.

Keeling, C.D., J.F.S. Chin, and T.P. Whorf. 1996. Increased activity of northern vegetation inferred from atmospheric CO_2 measurements. Nature 382:146–149.

Kimball, B.A., K. Kobayashi, and M. Bindi. 2002. Responses of agricultural crops to free-air CO_2 enrichment. Adv. Agron. 77:293–368.

Kobiljski, B., and S. Dencic. 2001. Global climate change: challenge for breeding and seed production of major field crops. J. Genet. Breed. 55(1):83–90.

Krupinsky, J.M., K.L. Bailey, M.P. McMullen, B.D. Gossen, and T.K. Turkington. 2002. Managing plant disease risk in diversified cropping systems. Agron. J. 94:198–209.

Larney, F.J., C.W. Lindwall, R.C. Izaurralde, and A.P. Moulin. 1994. Tillage systems for soil and water conservation on the Canadian

Prairie. p. 305–328. *In* Conservation tillage in temperate agroecosystems. CRC Press, Boca Raton, FL.

Laurila, H. 2001. Simulation of spring wheat responses to elevated CO_2 and temperature by using CERES-wheat crop model. Agric. Food Sci. Finl. 10:175–196.

Lawson, B.D. 2003. Trends in winter extreme minimum temperature on the Canadian Prairie. Atmos-Ocean 41(3):233–239.

Lean, J., and D. Rind. 1998. Climate forcing by changing solar radiation. J. Clim. 11:3069–3094.

Lemmen, D.S., and F.J. Warren. 2004. Climate change impacts and adaptation: a Canadian perspective. Available at http://adaptation.nrcan.gc.ca/perspective/index_e.php [verified 31 Aug. 2007]. Natural Resources Canada, Ottawa, ON.

Leport, L., N.C. Turner, R.J. French, D. Tennent, B.D. Thomson, and K.H.M. Siddique. 1998. Water relations, gas exchange and growth of cool-season grain legumes in a Mediterranean-type environment. Eur. J. Agron. 9:295–303.

Martens, J.W., W.L. Seaman, and T.G. Atkinson. 1984. Diseases of field crops in Canada. Can. Phytopathological Soc., Harrow, ON, Canada.

McCarthy, J.J., O.F. Canziani, N.A. Leary, D.J. Dokken, and K.S. White. (Eds.) 2001. Climate Change 2001: Impacts, Adaptation, and Vulnerability. Cambridge Univ. Press, Cambridge, UK.

McGinn, S.M., and A. Shepherd. 2003. Impact of climate change scenarios on the agroclimate of the Canadian prairies. Can. J. Soil Sci. 83:623–630.

McKenzie, R.H., A.B. Middleton, N. Flore, and E. Bremer. 2004. Evapotranspiration efficiency of pea in south and central Alberta. Can. J. Plant Sci. 84(2):473–476.

Miller, P., S. Brandt, A. Slinkard, C. McDonald, D. Derksen, and J. Waddington. 1998. New crop types for diversifying and extending spring wheat rotations in the Brown and Dark Brown soil zones of Saskatchewan. Project Rep. Agric. Agri-Food Can., Swift Current, SK.

Miller, P.R., C.L. McDonald, D.A. Derksen, and J. Waddington. 2001. The adaptation of seven broadleaf crops to the dry semiarid prairie. Can. J. Plant Sci. 81:29–43.

Miller, P.R., B.G. McConkey, G.W. Clayton, S.A. Brandt, J.A. Staricka, A.M. Johnston, G.P. Lafond, B.G. Schatz, D.D. Baltensperger, and K.E. Neill. 2002a. Pulse crop adaptation in the Northern Great Plains. Agron. J. 94:261–272.

Miller, P.R., J. Waddington, C.L. McDonald, and D.A. Derksen. 2002b. Cropping sequence affects wheat productivity on the semiarid Northern Plains. Can. J. Plant Sci. 82:307–318.

Miller, P.R., Y. Gan, B.G. McConkey, and C.L. McDonald. 2003a. Pulse crops for the Northern Great Plains: I. Grain productivity and residual effects on soil water and nitrogen. Agron. J. 95:972–979.

Miller, P.R., Y. Gan, B.G. McConkey, and C.L. McDonald. 2003b. Pulse crops for the Northern Great Plains: II. Cropping sequence effects on cereal, oilseed, and pulse crops. Agron. J. 95:980–986.

Miller, P.R., and J.A. Holmes. 2005. Cropping sequence effects of four broadleaf crops on four cereal crops in the Northern Great Plains. Agron. J. 97:189–200.

Motha, R.P., and W. Baier. 2005. Impacts of present and future climate change and climate variability on agriculture in the temperate regions: North America. Clim. Change 70:137–164.

Myneni, R.B., C.D. Keeling, C.J. Tucker, G. Asrar, and R.R. Nemani. 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. Nature 386:698–702.

Ney, B., and O. Turc. 1993. Heat-unit-based description of the reproductive development of pea. Crop Sci. 33:510–514.

Nielsen, D.C. 2001. Production functions for chickpea, field pea, and lentil in the central Great Plains. Agron. J. 93:563–569.

Nielsen, D.C., P.W. Unger, and P.R. Miller. 2005. Efficient water use in dryland cropping systems in the Great Plains. Agron. J. 97:364–372.

Padbury, G., S. Waltman, J. Caprio, G. Coen, S. McGinn, D. Mortenson, G. Nielsen, and R. Sinclair. 2002. Agroecosystems and land resources of the Northern Great Plains. Agron. J. 94:251–261.

Parmesan, C., and G. Yohe. 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature 421:37–42.

Phillips, D.L., J.J. Lee, and R.F. Dodson. 1996. Sensitivity of the US corn belt to climate change and elevated CO_2: I. Corn and soybean yields. Agric. Syst. 52:481–502.

Raddatz, R., J. Maybank, and G.B. Atkinson. 1991. Mean daily temperature normals from 1901-30 to 1961-90 on the eastern Canadian Prairies. Clim. Bull. 25:118–123.

Raper, C.D., Jr., and P.J. Kramer. 1987. Stress physiology. p. 589-641. *In* J.R. Wilcox (ed.) Soybeans: Improvement, production and uses. 2nd ed. Agron. Monogr. 16. ASA, CSSA, and SSSA, Madison, WI.

Reilly, J., F. Tubiello, B. McCarl, D. Abler, R. Darwin, K. Fuglie, S. Hollinger, C. Izaurralde, S. Jagtap, J. Jones, L. Mearns, D. Ojima, E. Paul, K. Paustian, S. Riha, N. Rosenberg, and C. Rosenzweig. 2003. U.S. agriculture and climate change: new results. Clim. Change 57:43–69.

Roberts, E.H., R.J. Summerfield, R.H. Ellis, and K.A. Stewart. 1988. Photothermal time for flowering in lentils (*Lens culinaris*) and the analysis of potential vernalization responses. Ann. Bot. 61:29–39.

Root, T.L., J.T. Price, K.R. Hall, S.H. Schneider, C. Rosenzweig, and J.A. Pounds. 2003. Fingerprints of global warming on wild animals and plants. Nature 421:57–60.

Rosenberg, N.J., R.A. Brown, R.C. Izaurralde, and A.M. Thomson. 2003. Integrated assessment of Hadley Centre (HadCM2) climate change projections on agricultural productivity and irrigation water supply in the conterminous United States. I. Climate change scenarios and impacts on irrigation water supply simulated with the HUMUS model. Agric. For. Meteor. 117:73–96.

Saskatchewan Pulse Growers. 2000. Pulse production manual. 2nd ed. Saskatchewan Pulse Growers, Saskatoon, SK, Canada.

Sauchyn, D.J., E.M. Barrow, R.F. Hopkinson, and P.R. Leavitt. 2002. Aridity on the Canadian Plains. Géographie physique et Quaternaire 56(2–3):247–259.

Sauchyn, D., E. Barrow, R. Hopkinson, and P. Leavitt. 2003. Aridity on the Canadian Plains: Future trends and past variability. Summary Document. p. 12. Prairie Adaptation Research Collaborative (PARC), University of Regina, Regina, SK.

Schneider, S.H. 1994. Detecting climatic change signals: Are there any "fingerprints"? Science 263:341–347.

Shen, S.S.P., H. Yin, K. Cannon, A. Howard, S. Chetner, and T.R. Karl. 2005. Temporal and spatial changes of the agroclimate in Alberta, Canada, from 1901 to 2002. J. Appl. Meteorol. 44(7):1090–1105.

Shepherd, A., and S.M. McGinn. 2003. Assessment of climate change on the Canadian Prairies from downscaled GCM data. Atmosphere-Ocean 41:301–316.

Siddique, K.H.M., K.L. Regan, D. Tennant, and B.D. Thomson. 2001. Water use and water use efficiency of cool season grain legumes in low rainfall Mediterranean-type environments. Eur. J. Agron. 15 (4):267–280.

Siddoway, F.H. 1970. Barriers for wind erosion control and water conservation. J. Soil Water Conserv. 25:180–184.

Skinner, W.R., and D.W. Gullet. 1993. Trends of daily maximum and minimum temperature in Canada during the past century. Clim. Bull. 27:63–77.

Skinner, W.R., and J.A. Majorowicz. 1999. Regional climatic warming and associated twentieth century land-cover changes in northwestern North America. Clim. Res. 12:39–52.

Smith, D.L., and J.J. Almaraz. 2004. Climate change and crop production: contributions, impacts, and adaptations. Can. J. Plant Pathol. 26:253–266.

Smit, B., and M.W. Skinner. 2002. Adaptation options in agriculture to climate change: a typology. Mitig. Adapt. Strategies Glob. Change 7:85–114.

Soltani, A., G.L. Hammer, B. Torabi, M.J. Robertson, and E. Zeinali. 2006. Modeling chickpea growth and development: phenological development. Field Crops Res. 99:1–13.

Srinivasan, A., C. Johansen, and N.P. Saxena. 1998. Cold tolerance during early reproductive growth of chickpea (*Cicer arietinum* L.): Characterization of stress and genetic variation in pod set. Field Crops Res. 57:181–193.

Steppuhn, H. 1994. Snowcover retention capacities for direct-combined wheat and barley stubble in windy environments. Can. Agric. Eng. 36:215–223.

Summerfield, R.J., R.H. Ellis, and E.H. Roberts. 1989. Vernalization in chickpea (*Cicer arietinum*): Fact of artifact? Ann. Bot. 64:599–603.

Swenson, J.B., and G.A. Murray. 1983. Cold acclimation of field peas in a controlled environment. Crop Sci. 23:27–30.

Thomson, A.M., R.A. Brown, N.J. Rosenberg, R.C. Izaurralde, and V. Benson. 2005. Climate change impacts for the conterminous USA:

an integrated assessment—Part 3. Dryland production of grain and forage crops. Clim. Change 69(1):43–65.

Turner, N.C., G.C. Wright, and K.H.M. Siddique. 2001. Adaptation of grain legumes (pulses) to water-limited environments. Adv. Agron. 71:193–231.

Turner, N.C., S.L. Davies, J.A. Plummer, and K.H.M. Siddique. 2005. Seed filling in grain legumes under water deficits, with emphasis on chickpeas. Adv. Agron. 87:211–250.

Wang, J., Y.T. Gan, F. Clarke, and C.L. McDonald. 2006. Response of chickpea yield to high temperature stress during reproductive development. Crop Sci. 46:2171–2178.

Walther, G.-R., E. Post, P. Convey, A. Menzel, C. Parmesan, T.J.C. Beebee, J.-M. Fromentin, O. Hoegh-Guldberg, and F. Bairlein. 2002. Ecological responses to recent climate change. Nature 416:389–395.

Welbaum, G.E., D. Bian, D.R. Hill, R.L. Grayson, and M.K. Gunatilaka. 1997. Freezing tolerance, protein composition, and abscisic acid localization and content of pea epicotyl, shoot, and root tissue in response to temperature and water stress. J. Exp. Bot. 48:643–654.

Wery, J., O. Turc, and J. Lecoeur. 1993. Mechanisms of resistance to cold, heat and drought in cool-season legumes, with special reference to chickpea and pea. p. 271–292. *In* K.B. Singh and M.C. Saxena (ed.) Breeding for stress tolerance in cool-season food legumes. John Wiley & Sons, Chichester, UK.

Wheaton, E.E. 1990. Frequency and severity of drought and dust storms. Can. J. Agric. Econ. 38:695–700.

White, J.W., G.S. McMaster, and G.O. Edmeades. 2004. Physiology, genomics and crop response to global change. Field Crops Res. 90:1–3.

Wiese, M.V., W.J. Kaiser, L.J. Smith, and F.J. Muehlbauer. 1995. Ascochyta blight of chickpea. Agric. Exp. Stn. Bull. CIS 886 (rev.) Univ. of Idaho Coop Ext. Syst., Moscow, ID.

Yu, M., Q. Gao, and M.J. Shaffer. 2002. Simulating interactive effects of symbiotic nitrogen fixation, carbon dioxide elevation, and climatic change on legume growth. J. Environ. Qual. 31(2):634–641.

Zentner, R.P., C.A. Campbell, V.O. Biederbeck, P.R. Miller, F. Selles, and M.R. Fernandez. 2001. In search of sustainable cropping system for the semiarid Canadian prairies. J. Sust. Agri. 18:117–136.

Zentner, R.P., D.D. Wall, C.N. Nagy, E.G. Smith, D.L. Young, P.R. Miller, C.A. Campbell, B.G. McConkey, S.A. Brandt, G.P. Lafond, A.M. Johnston, and D.A. Derksen. 2002. Economics of Crop Diversification and Soil Tillage Opportunities in the Canadian Prairies. Agron. J. 94:216–230.

Zhang, H., M. Pala, T. Oweis, and H. Harris. 2000a. Water use and water-use efficiency of chickpea and lentil in a Mediterranean environment. Aust. J. Agric. Res. 51:295–304.

Zhang, X., L.A. Vincent, W.D. Hogg, and A. Niitsoo. 2000b. Temperature and precipitation trends in Canada during the 20th century. Atmos. Ocean 38:395–429.

Zhou, L., C.J. Tucker, R.K. Kaufmann, D. Slayback, N.V. Shabanov, and R.B. Myneni. 2001. Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999. J. Geophys. Res. 106:20,069–20,083.

Ziska, L.H., J.A. Bunce, and F. Caulfield. 1998. Intraspecific variation in seed yield of soybean (*Glycine max*) in response to increased atmospheric carbon dioxide. Aust. J. Plant Physiol. 25:801–807.

Ziska, L.H., and J.A. Bunce. 2000. Sensitivity of field-grown soybean to future atmospheric CO_2: selection for improved productivity in the 21st century. Aust. J. Plant Physiol. 27:979–984.

Ziska, L.H., J.A. Bunce, and F.A. Caulfield. 2001. Rising atmospheric carbon dioxide and seed yield of soybean genotypes. Crop Sci. 41:385–391.